

VERY METAL-POOR STARS IN THE OUTER GALACTIC BULGE FOUND BY THE APOGEE SURVEY

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Draft version December 11, 2013

ABSTRACT

Despite its importance for understanding the nature of early stellar generations and for constraining Galactic bulge formation models, at present little is known about the metal-poor stellar content of the central Milky Way. This is a consequence of the great distances involved and intervening dust obscuration, which challenge optical studies. However, the Apache Point Observatory Galactic Evolution Experiment (APOGEE), a wide-area, multifiber, high-resolution spectroscopic survey within Sloan Digital Sky Survey III (SDSS-III), is exploring the chemistry of all Galactic stellar populations at infrared wavelengths, with particular emphasis on the disk and the bulge. An automated spectral analysis of data on 2,403 giant stars in twelve fields in the bulge obtained during APOGEE commissioning yielded five stars with low metallicity ($[\text{Fe}/\text{H}] \leq -1.7$), including two that are very metal-poor $[\text{Fe}/\text{H}] \sim -2.1$ by bulge standards.

Luminosity-based distance estimates place the five stars within the outer bulge, where other 1,246 of the analyzed stars may reside. A manual reanalysis of the spectra verifies the low metallicities, and finds these stars to be enhanced in the α -elements O, Mg, and Si without significant α -pattern differences with other local halo or metal-weak thick-disk stars of similar metallicity, or even with other more metal-rich bulge stars. While neither the kinematics nor chemistry of these stars can yet definitively determine which, if any, are truly bulge members, rather than denizens of other populations co-located with the bulge, the newly-identified stars reveal that the chemistry of metal-poor stars in the central Galaxy resembles that of metal-weak thick-disk stars at similar metallicity.

Subject headings: stars: abundances — stars: atmospheres — Galaxy: center — Galaxy: structure

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1. INTRODUCTION

The chemical compositions of the oldest stars hold fundamental clues about the early history of galaxies. Even if no true Population III stars presently exist in the Milky Way, their nature can be constrained from observations of the elemental abundance patterns of the most metal-poor existing Galactic stars (e.g., Beers & Christlieb 2005; Ekström et al. 2008). Theoretical predictions suggest that the oldest, most metal-poor stars in the Milky Way (MW) are to be found in the bulge (e.g., White & Springel 2000; Tumlinson 2010). However, these ancient relics are extremely difficult to identify because of the combination of very high extinction, foreground contamination, and the fact that the most metal-poor stars are but a small fraction of a large population of stars located in the inner Galaxy. As a result, our view of the early stages of Galactic formation and chemical evolution has been skewed by studies of more easily accessible Galactic halo samples, at large Galactocentric distances.

To date, the origin of the Galactic bulge is still uncertain. The boxy X-shape (e.g., McWilliam & Zoccali 2010) and high metallicity (e.g., Rich 1988) of the bulge suggests secular formation associated with the disk and bar — i.e., a *pseudo*-bulge (e.g., Immeli et al. 2004; Kormendy & Kennicutt 2004). On the other hand, the metallicity gradient of the bulge seen by Zoccali et al. (2008) and its old age (~ 10 Gyr, Clarkson et al. 2008) are more consistent with a *classical* bulge (e.g., Rahimi et al. 2010; Bournaud et al. 2011). However, the above criteria are clearly not definitive model discriminators, given that: Kunder et al. (2012) also discuss metallicity gradients in a secular scenario, the high metallicity in the classical scenario could be explained by early starbursts (McWilliam & Rich 1994), and old age could be understood in a secular scenario if disk instabilities occurred at early times. Moreover, recent studies by Babusiaux et al. (2010) and Hill et al. (2011) suggest that the central MW may include the superposition of a classical bulge and a pseudo-bulge.

To discriminate between these formation scenarios, a comprehensive chemical analysis of the central MW is needed, to characterize the metal-poor end of its metallicity distribution function (MDF) and assess abundance patterns of bulge populations at all metallicities. The ratio between α -element and iron abundances ($[\alpha/\text{Fe}]^{20}$) of a stellar population is sensitive to the initial mass function of its parental population, whereas the position of the “knee” of the metallicity- $[\alpha/\text{Fe}]$ relation is sensitive to the early star formation rate (e.g., McWilliam 1997). The *spread* in $[\alpha/\text{Fe}]$ at given $[\text{Fe}/\text{H}]$ depends on whether the metal-poor bulge stars were accreted or produced *in situ*, and by which mechanisms (Immeli et al. 2004; Rahimi et al. 2010). Moreover, in the secular instability scenario, the bulge $[\alpha/\text{Fe}]$ pattern should resemble that of the inner disk. Unfortunately, this discriminatory power of chemical abundances has barely been exploited because most spectroscopic studies have been restricted to high metallicity bulge stars. For example, the pioneering medium-resolution optical study of twelve giants by McWilliam & Rich (1994) that discovered the bulge

to be α -enhanced (a signature of rapid formation) was limited to $[\text{Fe}/\text{H}] \geq -1.08$. Similar results were obtained from high-resolution, near-infrared spectroscopy of fourteen bulge giants with $[\text{Fe}/\text{H}] \sim -0.33$ by Rich & Origlia (2005), and seven more with $[\text{Fe}/\text{H}] \geq -1.05$ by Cunha & Smith (2006). Subsequent high-resolution optical analyses (e.g., dozens of stars by Fulbright et al. 2007, Zoccali et al. 2006, and Lecureur et al. 2007) — still probing only $[\text{Fe}/\text{H}] \geq -1.30$ — revealed a bulge that is more α -enhanced than the local thick disk. Starbursts were invoked to explain these higher α -element levels within a classical formation scenario. However, more recent studies comparing bulge with inner disk (Bensby et al. 2010), or thick-disk stars (and with more homogeneous analyses — Meléndez et al. 2008; Ryde et al. 2010; Alves-Brito et al. 2010; Gonzalez et al. 2011) *did* find common abundance patterns, which supports bulge formation scenarios invoking either secular evolution or radial stellar migrations associated with spiral arms and/or the bar (Schönrich & Binney 2009, but cf. Minchev et al. 2012).

A striking aspect of all previous spectroscopic surveys of the bulge is that despite sample sizes approaching a thousand stars, until only very recently the most metal-poor star identified had $[\text{Fe}/\text{H}] = -1.69$ (Zoccali et al. 2008), with only four stars having $[\text{Fe}/\text{H}] < -1.5$ known. Clearly, any hope of probing the extremely minor, but exceedingly interesting, metal-poor content of the central Galaxy requires much larger samples — a challenging prospect, given the significant distance and foreground dust obscuration. The situation is changing rapidly, the large ARGOS survey at medium-resolution recently reported $[\text{Fe}/\text{H}]$ and averaged $[\alpha/\text{Fe}]$ for stars in the inner Galaxy down to $[\text{Fe}/\text{H}] = -2.60$ (Ness et al. 2012). Here we report the discovery of five additional stars with $[\text{Fe}/\text{H}] \lesssim -1.5$ in the central Galaxy found within a sample of $\sim 2,403$ stars observed in bulge fields by the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2010), part of the Sloan Digital Sky Survey III (SDSS-III; Eisenstein et al. 2011), commissioning. APOGEE uses a high resolution, H -band spectrograph with 300 optical fibers mated to the large field-of-view, Sloan 2.5-m telescope (Gunn et al. 2006). We also present detailed abundance ratios for these stars and find that they are similar to metal-poor stars in other parts of the Galaxy.

2. OBSERVATIONS AND ABUNDANCE ANALYSIS

APOGEE commissioning observations were taken in May-July 2011 for $\sim 4,700$ K/M giant stars in 18 fields spanning $-1^\circ < l < 20^\circ$, $|b| < 20^\circ$, and $\delta > -32^\circ$ (see Nidever et al. 2012, Fig. 1). Stars were selected from the 2MASS Point Source Catalog (Skrutskie et al. 2006) by color ($|J - K_s|_0 \geq 0.5$) and magnitude ($H \leq 11.0$) (see Zasowski et al. 2013). The observed spectra were of high quality ($R = 22,500$, $S/N > 150$ per pixel, at near Nyquist sampling), although misplacement of the red detector led to degraded resolution ($R \sim 14,500$) for $1.65 < \lambda < 1.70 \mu\text{m}$. The raw datacubes were reduced to calibrated, 1-D spectra and stellar radial velocities (RVs) were derived using the APOGEE reduction pipeline (Nidever et al. 2012). Effective temperatures (T_{eff}), surface gravities ($\log g$), and $[\text{Fe}/\text{H}]$ from an early version of the APOGEE Stellar Parameter and Chemical Abundances Pipeline (ASPCAP, García Pérez

²⁰ $[\text{X}/\text{Fe}] = A(\text{X}) - A(\text{X})_\odot - (A(\text{Fe}) - A(\text{Fe})_\odot)$, $A(\text{X}) = \log(N_{\text{X}}/N_{\text{H}}) + 12$, where N_{X} represents the number density of nuclei of element X.

TABLE 1
DERIVED STELLAR PARAMETERS AND ABUNDANCES FOR THE METAL-POOR BULGE CANDIDATES.

2MASS Star ID =	17062946-2325097	17083699-2257328	17324728-1735240	18013387-1907266	18155672-2133077
l [°]	359.727099	0.396365	8.108990	10.301410	9.811497
b [°]	10.358167	10.228863	8.491406	1.842886	-2.282258
α_{2000} [h m s]	17 06 29.46	17 08 36.99	17 32 47.28	18 01 33.87	18 15 56.72
δ_{2000} [h m s]	-23 25 09.7	-22 57 32.8	-17 35 24.0	-19 07 26.6	-21 33 07.7
H [mag]	9.38	9.794	9.686	9.665	8.828
A_{Ks} [mag]	0.319	0.293	0.247	0.607	0.275
V_{helio} [km s ⁻¹]	-39.49	328.49	21.03	142.17	-49.79
d [kpc]	9.43	8.37	9.64	7.40	5.71
S/N	403	326	230	159	251
T_{eff} [K]	3900 (± 150)	4300 (± 150)	4200 (± 150)	4000 (± 150)	4100 (± 150)
$\log g$ [cgs]	0.36 (± 0.50)	0.70 (± 0.50)	0.55 (± 0.50)	0.52 (± 0.50)	0.63 (± 0.50)
[Fe/H]	-1.47 (± 0.20)	-2.10 (± 0.20)	-2.05 (± 0.20)	-1.54 (± 0.20)	-1.66 (± 0.20)
ξ_t [km s ⁻¹]	3.0 (± 0.5)	2.5 (± 0.5)	2.5 (± 0.5)	2.5 (± 0.5)	2.5 (± 0.5)
$A(Fe)$	5.98 (± 0.12)	5.35 (± 0.12)	5.40 (± 0.12)	5.91 (± 0.12)	5.79 (± 0.12)
$A(O)$	7.72 (± 0.38)	7.04 (± 0.38)	7.13 (± 0.38)	7.75 (± 0.38)	7.42 (± 0.38)
$A(Mg)$	6.23 (± 0.15)	5.76 (± 0.15)	5.71 (± 0.15)	6.30 (± 0.15)	6.12 (± 0.15)
$A(Si)$	6.15 (± 0.10)	5.58 (± 0.10)	5.57 (± 0.10)	6.36 (± 0.10)	6.18 (± 0.10)
[O/Fe]	+0.53 ($^{+0.28}_{-0.26}$)	+0.48 ($^{+0.28}_{-0.26}$)	+0.52 ($^{+0.28}_{-0.26}$)	+0.63 ($^{+0.28}_{-0.26}$)	+0.42 ($^{+0.28}_{-0.26}$)
[Mg/Fe]	+0.17 ($^{+0.09}_{-0.07}$)	+0.33 ($^{+0.09}_{-0.07}$)	+0.23 ($^{+0.09}_{-0.07}$)	+0.31 ($^{+0.09}_{-0.07}$)	+0.25 ($^{+0.09}_{-0.07}$)
[Si/Fe]	+0.11 ($^{+0.05}_{-0.08}$)	+0.17 ($^{+0.05}_{-0.08}$)	+0.11 ($^{+0.05}_{-0.08}$)	+0.39 ($^{+0.05}_{-0.08}$)	+0.33 ($^{+0.05}_{-0.08}$)

et al.2013, in prep.) were used to select candidate metal-poor stars in 12 bulge commissioning fields within 10.5° from the Galactic center. Six stars were selected as having $[Fe/H]_{ASPCAP} \leq -1.7$, but one was rejected from further consideration for showing peculiar line profiles (potentially a spectroscopic binary). Specific sections of the APOGEE spectra of the five metal-poor stars (Table 1) were then re-analyzed interactively via a classical 1D-LTE spectrum synthesis approach (see Fig. 1). The synthesis used MARCS model atmospheres (Asplund et al. 1997), computed for the individual stellar parameters and chemical compositions listed in Table 1. Equipped with the model atmospheres, stellar spectra were synthesized using the Uppsala code BSYN and a line list (version 201202161204) compiled specifically for APOGEE (Shetrone et al. 2013, in prep.). Both the instrumental and macroturbulence profiles were described by Gaussians whose widths were adjusted to the variable instrumental resolution ($\lambda/\Delta\lambda = 12,000$ – $22,000$). Following Meléndez et al. (2008), several iterations were performed to ensure consistency between the derived chemical compositions and those of the model atmospheres employed.

Initial estimates of the atmospheric parameters were based on the observed spectra, in combination with theoretical isochrones. To determine T_{eff} , the ratio (R_{OH-Mg}) of the sum of OH line strengths (at $1.57589 \mu m$ and $1.57608 \mu m$) to that of a nearby Mg I line (at $1.57533 \mu m$) was measured.²¹ R_{OH-Mg} is quite sensitive to T_{eff} , due to the strong temperature dependence of OH for $T_{eff} \gtrsim 4500$ K, with only a small dependence on $\log g$. We calibrated R_{OH-Mg} versus T_{eff} using data for the field red giants α Boo, μ Leo, β And, and δ Oph, and giants from the globular clusters M3, M13, and M71. Though spanning a large range in metallicity, age, and mass, these particular stars define an R_{OH-Mg} - T_{eff} relation with an intrinsic scatter of only $\sim \pm 100$ – 120 K.

Surface gravities were derived from isochrones (Dotter et al. 2008) with an assumed age of 10 Gyr and

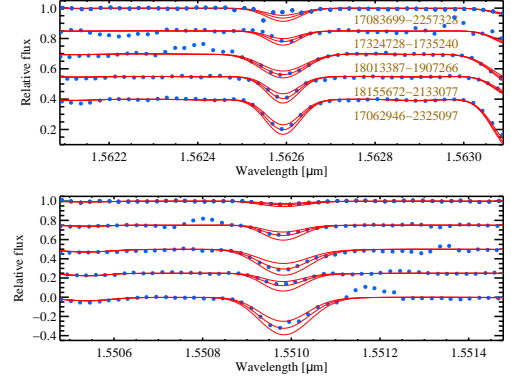


FIG. 1.— Observed (circles) and synthetic (solid line) spectra of the Fe I 1.56259 μm (top panel) and OH lines at $\sim 1.5510 \mu m$ (bottom panel) for the five metal-poor stars in our study. Spectra were offset vertically by multiples of 0.15 (Fe) and 0.25 (OH) for clarity. The synthesis for the best-fitting abundance and ± 0.2 dex from that are also shown.

$[\alpha/Fe]=+0.6$ (consistent with our final derived values). The adopted values of T_{eff} and $\log g$ for the stars are given in Table 1, and were checked using the temperature and gravity-sensitive profiles of H I lines at $1.61137 \mu m$ and $1.68111 \mu m$, with theoretical line absorption profiles from Ali & Griem (1966).

Stellar metallicity estimates ($[Fe/H]$) are based on mean values of iron abundance derived from a sample of four to thirteen measured Fe I lines, and assuming a solar abundance value of $A(Fe)_\odot=7.45$ (Asplund et al. 2005). For the other elements, values of $A(O)_\odot=8.66$, $A(Mg)_\odot=7.58$, and $A(Si)_\odot=7.55$ (Asplund et al. 2005) were assumed. The lines were selected from the ASPCAP line list among those with minimum blending from molecular lines in the atmospheric parameter range explored in this study. Sample spectra and synthesis for the Fe I 1.56259 μm line are shown in Figure 1.

Microturbulent velocities (ξ_t) were derived by forcing consistency between the abundances obtained from weak and strong Mg and Si lines. The lines used were the following: Mg I 1.57450, 1.57533, 1.57700, and 1.59588 μm ,

²¹ Cited wavelengths refer to vacuum measurements.

TABLE 2
ABUNDANCE SENSITIVITY TO STELLAR PARAMETER UNCERTAINTIES.

	$A(\text{Fe})$	$A(\text{O})$	$A(\text{Mg})$	$A(\text{Si})$
$\Delta T_{\text{eff}} (+150 \text{ K})$	0.090	0.276	0.090	0.072
(-150 K)	-0.084	-0.258	-0.090	-0.042
$\Delta \log g (0.5) [\text{cgs}]$	-0.008	-0.110	-0.060	0.000
$(-0.5) [\text{cgs}]$	0.032	0.140	0.050	0.015
$\Delta \xi_t (0.5 \text{ km s}^{-1})$	-0.008	-0.006	-0.080	-0.050
(-0.5 km s^{-1})	0.016	0.006	0.080	0.070
$\Delta [\text{Fe}/\text{H}] (0.2 \text{ dex})$	0.003	0.120	-0.007	0.006
(-0.2 dex)	0.007	-0.100	0.005	0.000

and Si I 1.59644, 1.60992, 1.66853, and 1.66853 μm . We obtain $\xi_t = 2.5 \text{ km s}^{-1}$ for all stars (except one with 3.0 km s^{-1}).

The oxygen abundances were obtained from the analysis of 10 to 17 OH lines covering $\lambda\lambda = 1.5395\text{--}1.6376 \mu\text{m}$. The mean abundance values are listed in Table 1, and the observed and synthetic spectra of OH lines at $\sim 1.5510 \mu\text{m}$ are shown in Fig. 1 for all stars. Because there may be some interdependence of O and C abundances through CO formation, our determinations require *a priori* knowledge of C abundances, which were estimated from very weak CO bands, and the non-detection of the C I atomic line at $1.68950 \mu\text{m}$ in any of the stars.

Internal errors in the abundances were derived from the abundance sensitivity to stellar parameters (Table 2) using the star 2M17083699-2257328 as a baseline and adopting the values listed in Table 2 as our uncertainties in the other parameters. For all elements, and oxygen in particular, abundance uncertainties are most sensitive to errors in T_{eff} . Overall, the abundances show moderate sensitivity to errors in $\log g$ (typically $\Delta A(X) < 0.1 \text{ dex}$), and are similarly or less sensitive to uncertainties in microturbulence and $[\text{Fe}/\text{H}]$. Final uncertainties were computed by adding the errors in quadrature and are 0.12, 0.38, 0.15, and 0.10 dex for Fe, O, Mg, and Si, respectively.

3. POPULATION MEMBERSHIP

The stars in Table 1 have (l, b) typical of the outer bulge, as do ~ 1246 other automatically-analyzed stars in our sample, but it is unclear whether the stars in that table are actually in, and belong to, the bulge. To gauge distances, luminosities were estimated from the adopted $\log g$ and derived T_{eff} , assuming $M=0.8 M_{\odot}$, as expected for old giants. To determine M_H , bolometric corrections were estimated from T_{eff} using a calibration derived from stellar isochrones in Girardi et al. (2000). Extinctions were estimated by combining near- and mid-IR photometry (Majewski et al. 2011) and the Indebetouw et al. (2005) extinction law. The derived distances (Table 1) have relatively large uncertainties, given the uncertainties in T_{eff} , gravities, assumed masses, and extinctions. Nevertheless, the distances — projected on the Galactic plane at $d/\cos(b)=5.71\text{--}9.59 \text{ kpc}$ — place these stars marginally or completely within the nominal bulge, assuming the latter has a $\sim 2\text{--}3 \text{ kpc}$ radius and $\sim 8 \text{ kpc}$ distance. However, both the Besançon (Robin et al. 2012) and Trilegal (Vanhollebeke et al. 2009) MW models predict that APOGEE target selection in these “bulge” fields should also yield a small number of metal-poor *halo* stars — though the expected ratio of metal-poor halo to

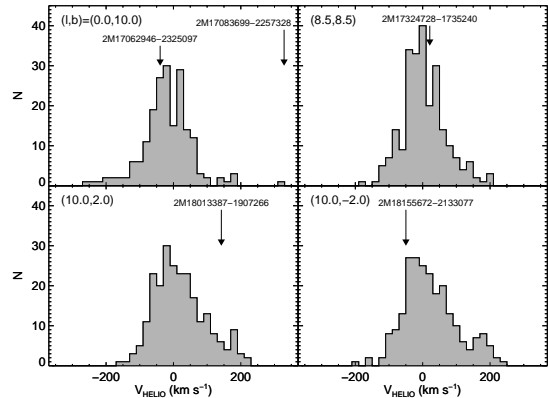


FIG. 2.— Heliocentric RV distributions for stars in the four observed bulge fields, with the velocities of the five metal-poor stars indicated.

bulge stars is presently unconstrained because it is highly dependent on uncertain extrapolations of the halo density law to small Galactocentric radii, as well as on the unknown shape of the bulge MDF. Moreover, RVs provide little additional discrimination between bulge and overlapping halo populations because of the similar (near zero) mean velocity and comparably large velocity dispersions of the two populations. The measured RVs are generally *compatible* with those of more metal-rich bulge stars dominating the samples in these fields (Fig. 2), although the star 2M17083699-2257328 has an extreme velocity ($V_{\text{hel}} = 328.5 \text{ km s}^{-1}$) compared to bulge stars in the same field ($\langle V_{\text{hel}} \rangle = -18.1 \text{ km s}^{-1}$, $\sigma_v = 53.4 \text{ km s}^{-1}$) and may therefore less likely be a bulge star on dynamical grounds. We conclude that, while our metal-poor stars are spatially coincident with the bulge-dominated, central Galaxy, we cannot definitively ascribe population membership to them by position or velocity.

4. THE IRON AND α -ELEMENT CONTENT OF THE METAL-POOR STARS

Even if as many as four of the five stars in this study are truly bulge members, they would represent a mere 0.17% of the 2,403 candidate red-giant stars targeted in the twelve bulge fields. Careful, detailed, analysis of the data confirmed their low metallicities, with three at $[\text{Fe}/\text{H}] \sim -1.6$, and two at $[\text{Fe}/\text{H}] \sim -2.1$. The metallicities derived here are robust ($[\text{Fe}/\text{H}]$ errors $\pm 0.11 \text{ dex}$), and comparable to, or lower than, the median metallicities of either local halo or metal-weak thick-disk stars, but certainly much more metal poor than the typical bulge star. Whether they are bulge, halo, or even thick-disk members, these stars are among the most metal poor ever found in the central parts of the Galaxy.

Our abundance estimates suggest that all five stars are α -enhanced, with mean abundance ratios and standard deviations $[\text{O}/\text{Fe}] = +0.52 \pm 0.08$, $[\text{Mg}/\text{Fe}] = +0.26 \pm 0.06$, and $[\text{Si}/\text{Fe}] = +0.22 \pm 0.13$. Figure 3 contains these derived $[\text{X}/\text{Fe}]$ (along with literature values — rescaled to our assumed solar abundances — for bulge, disk, and halo stars), and shows Si to have the most scatter (with perhaps a hint of two $[\text{Si}/\text{Fe}]$ subgroups), but oxygen to be most enhanced. A range of solar oxygen values exists in the literature (from different indicators and/or modeling); a different choice would have led to smaller or even larger enhancements. The $A(\text{O})$ are also the most uncertain because of the great sensitivity of molecular line

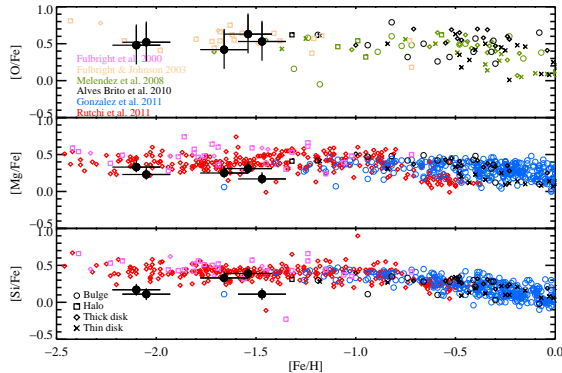


FIG. 3.— Comparison of our α -element measurements of the Table 1 stars (filled circles) with those from the literature for bulge, disk, and halo stars.

formation to atmospheric structure and, therefore, to the modeling employed in the spectral synthesis and to the adopted stellar parameters (especially T_{eff}). For abundance *ratios*, part of the sensitivity to stellar parameters is cancelled out, so that the $[\text{O}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$, and $[\text{Si}/\text{Fe}]$ internal errors shown in Figure 3 are reduced to $^{+0.28}_{-0.26}$, $^{+0.09}_{-0.07}$ and $^{+0.05}_{-0.08}$ dex, respectively.

With the exception of silicon, the α -enhancement abundances of our sample stars are not much different from those of other, previously reported “metal-poor bulge stars” shown in Figure 3, although the latter are almost entirely at higher metallicity and exhibit significant scatter. Three of our stars exhibit lower Si enhancements, but comparable to those seen in the only available literature datapoint for $[\text{Fe}/\text{H}] < -1.5$ (Gonzalez et al. 2011). However, the latter star also apparently has a peculiar, smaller Mg enhancement, a feature shared with none of our stars. Data for more metal-poor stars in the Galactic bulge are needed to confirm whether these particular enhancement variations are a distinctive feature of low-metallicity stars in the bulge.

Assuming our sample stars are true bulge members, it is interesting to compare their abundances with those of thick-disk stars. Fulbright et al. (2007) and Zoccali et al. (2006), deriving large α -enhancements for the bulge compared to published thick-disk abundances, argue for a higher star formation rate for the bulge, whereas the studies by Meléndez et al. (2008), Alves-Brito et al. (2010), and Gonzalez et al. (2011) (which analyzed stars from both populations homogeneously) claim no significant α -enhancement differences (§1). We can now extend these comparisons to lower metallicities using the disk data from Fulbright (2000), Fulbright & Johnson (2003)²², and Ruchti et al. (2011). Bear in mind that such a comparison, especially for oxygen (see García Pérez et al. 2006), should be viewed with caution because of potential systematic errors in the analyses: different abundance and stellar parameter scales, different stellar evolutionary stages, different abundance indicators, and different locations in the Galaxy. With these caveats, we find the abundances of our stars to be comparable to those of the metal-weak thick-disk stars in Figure 3. While (1) some of our Si abundances may be marginally too low, and (2) there are not many metal-

weak thick-disk points for comparison to our oxygen results, the metallicities and α -element abundance patterns of our low-metallicity stars are comparable to what is found in the metal-weak thick disk. This makes a somewhat stronger case for a possible connection between the bulge and thick disk, as suggested previously, and lends further support to the notion that migrating stars populated both the Galactic bulge and thick disk (Schönrich & Binney 2009).

The results in Table 1 indicate that these stars, as a group, do not have unusual $[\text{O}/\text{Fe}]$ values compared to those of halo stars, but may contain some members that have lower $[\text{Si}/\text{Fe}]$ and slightly lower $[\text{Mg}/\text{Fe}]$ values. Indeed, three of the stars have low values of $[\text{Si}/\text{Fe}]$ compared to most halo stars of similar metallicity, with one being 2M17083699-2257328, which has the most extreme RV and thus might be expected to be the most likely halo member. The two remaining stars cannot be chemically distinguished from local halo stars. It should be noted that Nissen & Schuster (2010) identified a population of α -poor halo stars. More data on the metal-poor populations of the inner Galaxy may help to disentangle possible metal-poor bulge stars from halo stars.

5. CONCLUSIONS

We have found five giant stars within the commissioning data of the SDSS-III’s APOGEE project that have sky positions and Galactic plane-projected distances ($d/\cos(b)=5.71\text{--}9.59$ kpc) expected for the bulge, but that exhibit distinctly low iron content ($-2.10 \leq [\text{Fe}/\text{H}] \leq -1.47$). We present abundance ratios for these stars, significantly augmenting the sample of metal-poor bulge stars with detailed chemical information and including two stars much more metal-poor ($[\text{Fe}/\text{H}] \sim -2.1$) than the previous bulge star with this information (a micro-lensed dwarf with $[\text{Fe}/\text{H}] = -1.89$, Bensby et al. 2012), which was excluded from our comparison of only giants.

There is no strong evidence that our stars are significantly chemically different from other more metal-rich bulge stars — or even different from other stars in the halo or metal-poor thick disk, although some stars in our sample do exhibit somewhat lower Si enhancements than typically seen in other Galactic stars at these metallicities. Unfortunately the presently available kinematics and chemistry are not sufficient to determine with certainty how many of the stars may be true bulge members. Nevertheless, this initial APOGEE sample significantly contributes to the task of compiling a more thorough census of the metal-poor stellar content of the central MW, and portends the promising results to be expected from the ongoing APOGEE exploration of the Galactic bulge.

We acknowledge funding from NSF grants AST11-09718 and AST-907873. Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III website is <http://www.sdss3.org/>. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona,

²² Oxygen abundances based only on the forbidden $[\text{O} \text{ I}]$ line at 630 nm were used from this source.

the Brazilian Participation Group, Brookhaven National Laboratory, University of Cambridge, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max

Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

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